UNCONFINED COMPRESSIVE STRENGTH OF A BITUMINOUS MIXTURE AND THE VISCOSITY OF THE BINDER

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by

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TECHNICAL PAPER

THE RELATIONSHIP BETWEEN THE UNCONFINED COMPRESSIVE STRENGTH

OF A BITUMINOUS MIXTURE AND THE VISCOSITY OF THE BINDER

TO: K. B. Woods, Director
Joint Highway Research Project

May 21, 1958

FROM: H. L. Michael, Assistant Director
Joint Highway Research Project

File No: 2-4-10
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Attached is a technical paper entitled, "The Relationship Between The Unconfined Compressive Strength of a Bituminous Mixture and The Viscosity of The Binder," by Professors L. E. Wood and W. H. Goetz of our staff. The paper has been prepared for the Proceedings of The Association of Asphalt Paving Technologists of 1958.

The paper is presented for the record.

Respectfully submitted,

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THE RELATIONSHIP BETWEEN THE UNCONFINED COMPRESSIVE STRENGTH OF A BITUMINOUS MIXTURE AND THE VISCOSITY OF THE BINDER

L. E. Wood and W. H. Goetz

INTRODUCTION

At last year's annual meeting of this Association the authors presented a paper which showed a relationship among temperature, rate of deformation, and unconfined compressive strength for a sheet-asphalt mixture. At that time, comments were made concerning the similarity between this relationship and various expressions that relate temperature and viscosity of a bituminous binder.

It was ~~is~~ the purpose of this study to: 1. Verify a means for expressing ~~the expression for~~ the effect of temperature and rate of deformation upon the unconfined compressive strength of a sheet-asphalt mixture, and 2. Determine the relationships existing between viscosity of the binder and unconfined compressive strength of a mixture at ~~the~~ various temperatures and rates of shear.

In the past, much effort has been directed toward determining the effect of the viscosity of the binder upon various physical properties of a bituminous-aggregate mixture. Weetman and Hurlburt (1) reported that a linear relationship resulted when the log of the Hubbard-Field stability was plotted against the log of the viscosity of the asphalt reclaimed from the mixture. The slope of the line was affected by crude source. Neppe (2) on the other hand reported, "the mechanical stability of a bituminous mixture at any temperature, is approximately a direct function (linear function) of the log log viscosity of the contained binder at that temperature and is independent of the source, nature and proportion of the latter constituent."

Fink and Lettier (3) found, in an investigation using asphaltic concrete, that a plot of log viscosity versus Marshall Stability (at an asphalt content of 6%) gave a linear expression. The test temperatures ranged from 100°F to 160°F.

The effect of temperature upon the viscosity of the binder has been expressed in several ways by many investigators: Vokac (4), Schweyer, Coombs, Traxler (5), Allen, Gibson (6), Lewis, Halstead (7), Nevitt (8), Cornelissen, Waterman (9). The choice of methods generally depends upon the temperature range in which one is working.

For expressing the effect of temperature upon mixture properties, Vokac (4) proposed a Mixture Susceptibility Index. This index stemmed from an expression Vokac obtained for representing the relationship between temperature and compressive strength: $\ln (p - c) = \ln a + b T$; where T = temperature, p = compressive strength, and a,b,c, are constants.

The investigation being reported here had an advantage over some of these earlier studies because of the recent introduction of the sliding plate microviscometer. This instrument permits one to obtain viscosity data not only at temperatures existing in the field but also at varying shear rates. The relationship between unconfined compressive strength of the mixture and viscosity of the binder can then be investigated for comparable rates of shear.

MATERIALS

The sand used in this study was a local material which met the gradation limits as set forth in ASTM D978-54, "Standard Specifications for Asphaltic Mixtures for Sheet Asphalt Paving," Surface Course Grading No. 2 (10). The sieve analysis of the sand is presented in Table 1 and depicted graphically in Figure 1. The control of the gradation was obtained by drying the sand, sieving it into the respective sizes and recombining it by weight in the desired proportions as shown in Table 1. The minus 200 material was obtained by adding pulverized limestone.

The asphaltic materials were generously supplied by the Whiting, Indiana refinery of the Standard Oil Company of Indiana through the cooperation of Dr. A. B. Brown and by the Texas Company at Port Neches, Texas through the cooperation of G. W. Robbins. The physical properties of the four asphalt cements used in this study are presented in Table 2. The viscosity data from which the viscosity values of Table 2 were extrapolated are presented in Table 3.

The asphalt content for the sand-asphalt mixtures was 9 percent by weight of total mixture. This value was obtained by using the Hubbard-Field design procedure.

Table 1

Sieve Analysis

Sieve Passing	Sieve Retained	Percent by Weight
No. 4	No. 8	0
No. 8	No. 16	7
No. 16	No. 50	34
No. 50	No. 100	27
No. 100	No. 200	15
No. 200		17

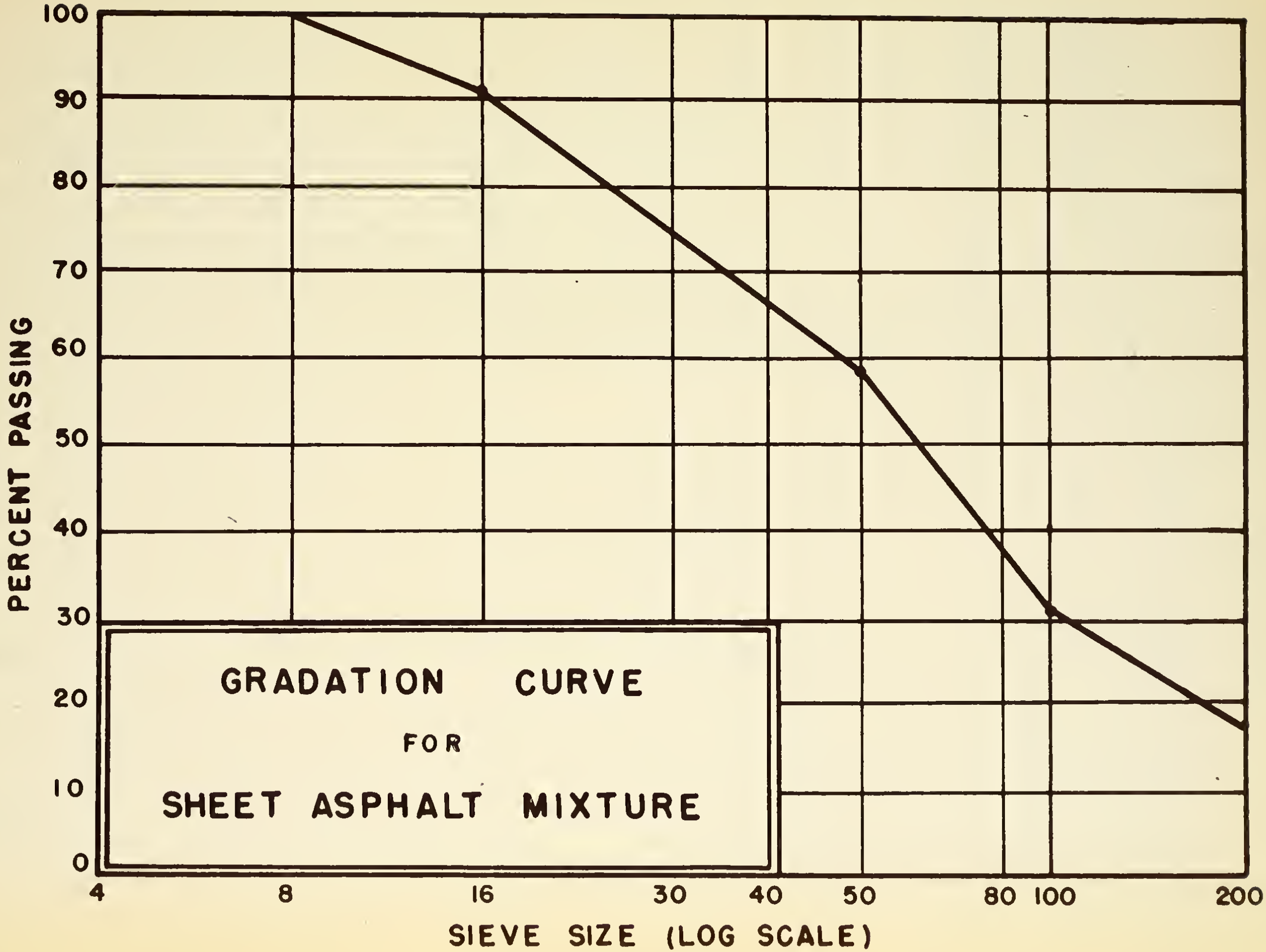
PERCENT PASSING
100
90
80
70
60
50
40
30
20
10
0
4
8
16
30
40
50
80
100
200
SIEVE SIZE (LOG SCALE)
GRADATION CURVE
FOR
SHEET ASPHALT MIXTURE

FIGURE 1

Table 2

Physical Properties of Asphalt Cements

		Asphalt A	Asphalt B	Asphalt C	Asphalt D
Penetration, 77°F, 100 gms, 5 sec.		66	65	64	93
Softening Point, °F		125	114	122	107
		Absolute Viscosity, Poises			
Temperature, °F	Shear Rate, sec.$^{-1}$	A	B	C	D
40	1×10^{-1}	5.2×10^{8}	2.0×10^{9}	1.3×10^{9}	9.0×10^{8}
	1×10^{-2}	6.8×10^{8}	2.0×10^{9}	1.3×10^{9}	9.0×10^{8}
	1×10^{-3}	8.8×10^{8}	2.0×10^{9}	1.3×10^{9}	9.0×10^{8}
100	1×10^{-1}	1.9×10^{5}	9.0×10^{5}	1.8×10^{5}	3.9×10^{4}
	1×10^{-2}	2.1×10^{5}	9.1×10^{5}	2.0×10^{5}	4.4×10^{4}
	1×10^{-3}	2.4×10^{5}	9.3×10^{5}	2.2×10^{5}	5.3×10^{4}
140	1×10^{-1}	4.1×10^{3}	1.3×10^{3}	3.4×10^{4}	9.5×10^{2}
	1×10^{-2}	4.7×10^{3}	3.4×10^{3}	8.3×10^{4}	2.3×10^{3}
	1×10^{-3}	5.4×10^{3}	9.5×10^{3}	2.0×10^{5}	5.5×10^{3}

Table 3

Viscosity Data for Asphalt Cements

Asphalt A

Temperature (°F)	Shear Rate (sec.$^{-1}$)	Viscosity (poises)
40	9.6×10^{-4}	9.0×10^{8}
	2.4×10^{-3}	8.1×10^{8}
100	1.6×10^{-2}	2.1×10^{5}
	8.2×10^{-2}	2.0×10^{5}
	5.4×10^{-1}	1.7×10^{5}
140	5.9×10^{-3}	5.1×10^{3}
	3.7×10^{-2}	4.2×10^{3}
	1.8×10^{-1}	4.0×10^{3}

Asphalt B

Temperature (°F)	Shear Rate (sec.$^{-1}$)	Viscosity (poises)
40	5.4×10^{-4}	2.0×10^{9}
	8.6×10^{-4}	2.0×10^{9}
100	2.0×10^{-2}	9.0×10^{4}
	3.6×10^{-2}	9.0×10^{4}
	1.0×10^{-1}	9.0×10^{4}
140	7.5×10^{-3}	4.0×10^{3}
	5.0×10^{-2}	1.7×10^{3}
	1.4×10^{-1}	1.1×10^{3}

Table 3 continued on page ~~7~~ 8

Table 3 (continued)

Asphalt C

Temperature (°F)	Shear Rate (sec.$^{-1}$)	Viscosity (poises)
40	6.5×10^{-4}	1.3×10^{9}
	1.4×10^{-3}	1.3×10^{9}
100	7.4×10^{-3}	2.0×10^{5}
	4.1×10^{-2}	1.9×10^{5}
	9.6×10^{-2}	1.8×10^{5}
140	8.2×10^{-3}	9.1×10^{3}
	3.5×10^{-2}	4.8×10^{3}
	1.5×10^{-1}	3.0×10^{3}

Asphalt D

Temperature (°F)	Shear Rate (sec.$^{-1}$)	Viscosity (poises)
40	2.1×10^{-4}	9.0×10^{8}
	1.8×10^{-3}	9.0×10^{8}
100	7.0×10^{-3}	4.8×10^{4}
	3.7×10^{-2}	4.1×10^{4}
	1.2×10^{-1}	4.0×10^{4}
140	2.0×10^{-2}	1.8×10^{3}
	8.6×10^{-2}	9.7×10^{2}
	2.5×10^{-1}	7.0×10^{2}

TESTING PROCEDURES

Since the major task of this study was to determine the relationship between the unconfined compressive strength of a bituminous mixture and the viscosity of the binder, it was necessary to choose a method of evaluating the binder viscosity under various temperatures and rates of shear ~~deformation~~. The parallel plate microviscometer seemed to be tailor-made in this regard. The method of evaluating the unconfined compressive strength of bituminous-aggregate mixtures has been well established in the past by Vokac (4) and Wood and Goetz (11).

Absolute Viscosity Determinations

The sliding plate microviscometer used in this study was a Hallikainen Model 1113A made available to the authors by the generous cooperation of the K. E. McConnaughay Asphalt Laboratory, Lafayette, Indiana. A water bath was used to control the test temperatures. In preparing the asphalt film on the glass plates, the asphalt cement was heated to approximately 300°F which was the same temperature used in liquifying the asphalt for preparing the sheet-asphalt specimens. The heated asphalt was placed on clean, glass plates and worked into a uniform layer with a thickness of approximately 50 microns. The prepared plates were cooled for one hour before being tested at the various temperatures. Varying loads were applied in order to obtain a range of shear rates at each of the test temperatures. For further information regarding viscosity determinations by means of a sliding plate microviscometer, the reader is directed to a paper authored by Griffin, Miles, Penther, and Simpson (12).

Unconfined Compression Tests

The mixtures used in this study were those in which the aggregate and asphalt were heated separately and then combined in a mixing operation. The aggregate was heated in an electric oven to a temperature of 325°F. The asphalts were heated in a gas oven to a temperature of 300°F.

The two constituents were mixed by hand in a heated porcelain bowl using a metal spoon for a period of two minutes and then molded into a specimen 2 inches in diameter and 4 inches in height by a double-plunger compaction method which included rodding the mixture into the mold. To control density of the specimens, care was taken to introduce a predetermined amount of material into the mold for compaction to the fixed height. The specimens were cured for two days in laboratory air at a temperature of 75 ± 5°F. The height, diameter, and weight of the specimens were then obtained for bulk density calculations.

Specimens were tested to failure at three rates of deformation: 0.2, 0.02, and 0.002 in./min. At each of these rates, three temperatures were used: 40, 100, and 140°F. These temperatures were maintained by means of a water bath.

RESULTS

In the first phase of this investigation, the absolute viscosities of the asphalt cements were determined at various shear rates and temperatures. In the second phase of this study, the unconfined compressive strengths of the various mixtures were determined at the different temperatures and rates of deformation.

Absolute Viscosity Determinations

The results of the viscosity tests on the various asphalts are presented in Tables 2 and 3 and depicted graphically in Figure 2 where the log of the viscosity expressed in poises is plotted against the log of the shear rate expressed in reciprocal seconds. At 40°F, the viscosity values of asphalts B, C, and D were unaffected by changes in shear rate, while asphalt A was affected slightly. At 100°F, the viscosity values of all four asphalts were affected slightly by changes in shear rate. At a temperature of 140°F, the viscosity of asphalt A was still affected only slightly by a change in shear rate while asphalts B, C, and D were quite sensitive to changes in shear rate. At all temperature levels asphalt A performed approximately as a Newtonian liquid while asphalts B, C, and D became more non-Newtonian as the temperatures increased. Since these various asphalts stem from different crude sources and production processes, it is obvious that these two variables are very important factors in determining the ~~mechanical~~ rheological properties of the end product.

The shear rates used for comparison of asphalt viscosity were chosen specifically so as to correspond with deformation rates used later in the

RELATIONSHIP BETWEEN
VISCOSITY AND SHEAR RATE
AT VARIOUS TEMPERATURES

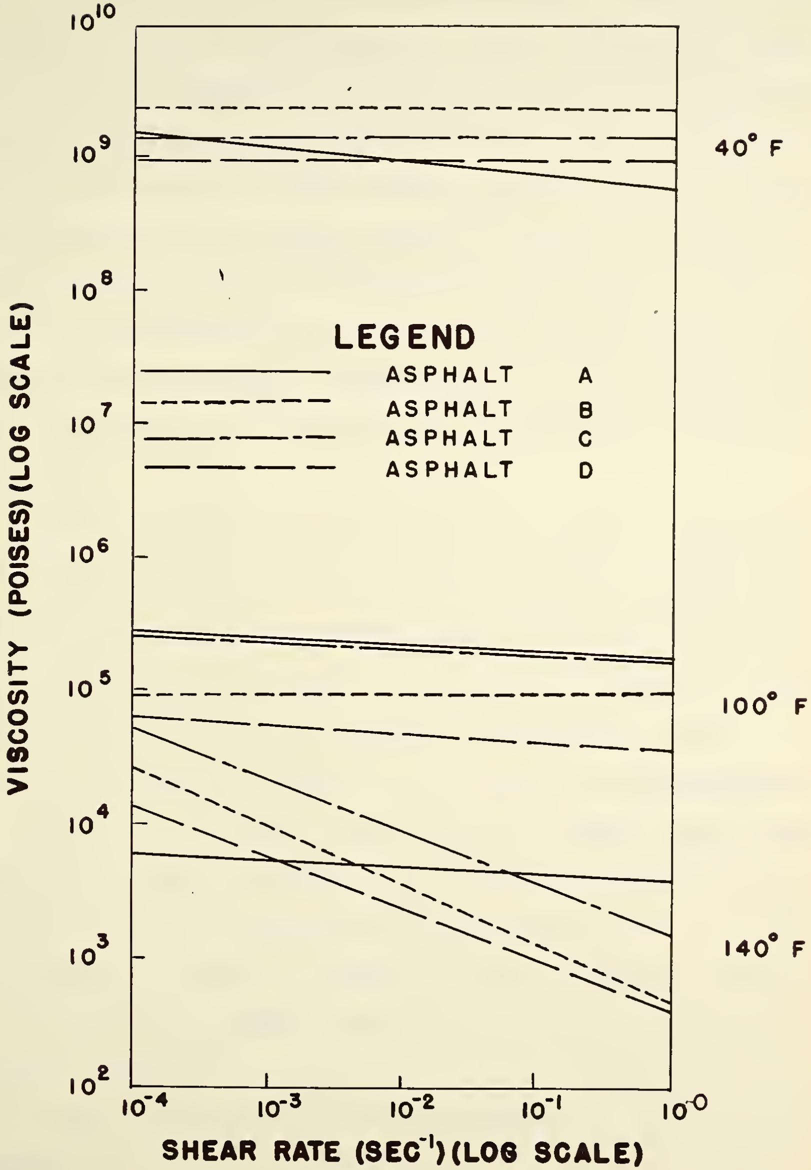

FIGURE 2

unconfined compression tests. For example, a rate of deformation of 0.2 inches per minute utilized on specimens four-inches high results in a rate of strain of 0.05 inches per inch per minute. Assuming an angle of internal friction of 30° results in a failure plane having an angle of 60° from the horizontal, 0.05 (the strain rate in the vertical sense) divided by 0.866 (the sine of 60°) gives a shear rate of 0.057 inches per inch per minute on the failure plane or 0.0095 reciprocal seconds. When developing the relationships between viscosity and unconfined compressive strength, the shear rate which was developed on the failure plane for the compression test was used to establish the consistency of the binder from the viscosity determinations. In order to obtain these values, the original viscosity data were extrapolated to the desired shear rates.

From Figure 2, it can be observed that for asphalt A, the relationship between log viscosity and log shear rate remains approximately the same at the three temperature levels. This fact becomes more obvious when one examines Figure 3 which is a plot of log log viscosity in poises versus temperature in degrees Fahrenheit at various shear rates for asphalt A. It can be seen that the three lines are approximately parallel.

From Figure 4, which is a plot of log log viscosity in poises versus temperature in degrees Fahrenheit, it can be seen that asphalt B gave a linear plot only for the temperature range of 40°F to 100°F. At 140°F the viscosity of asphalt B is affected by shear rate and the relationship of viscosity versus temperature becomes more non-linear as the shear rate decreases. Figures 5 and 6, which are plotted in the same manner, show that asphalts C and D react in a manner similar to that described above for asphalt B.

RELATIONSHIP BETWEEN TEMPERATURE AND VISCOSITY AT VARIOUS SHEAR RATES FOR ASPHALT A

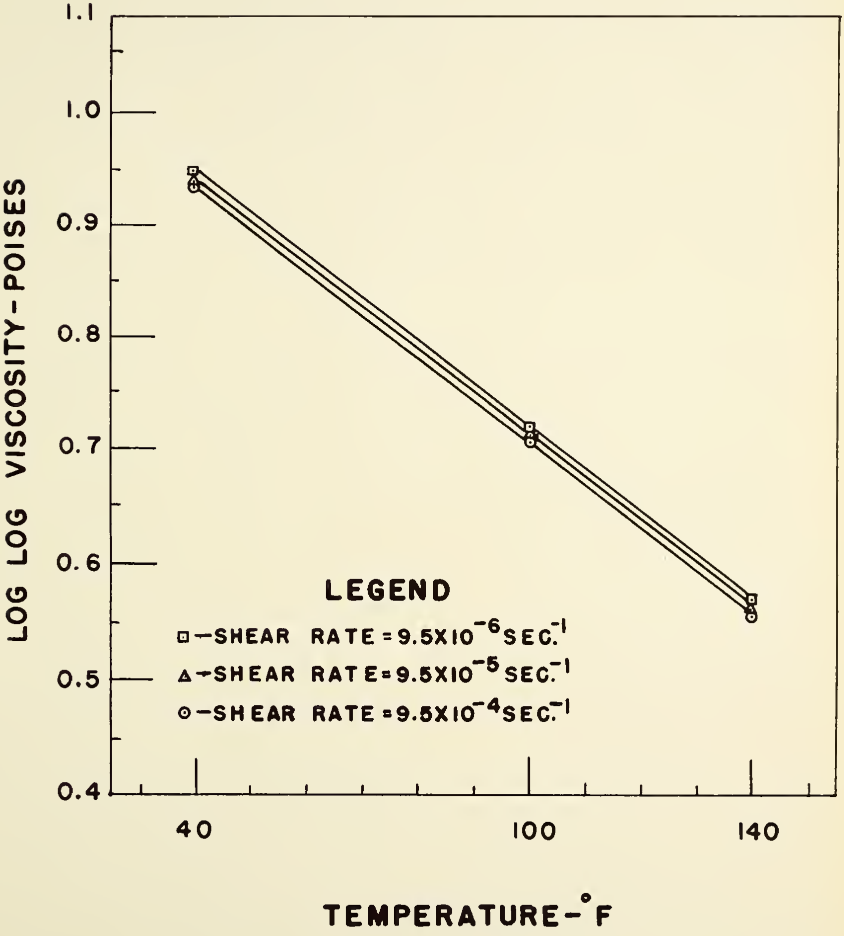

FIGURE 3

RELATIONSHIP BETWEEN TEMPERATURE AND VISCOSITY AT VARIOUS SHEAR RATES FOR ASPHALT B

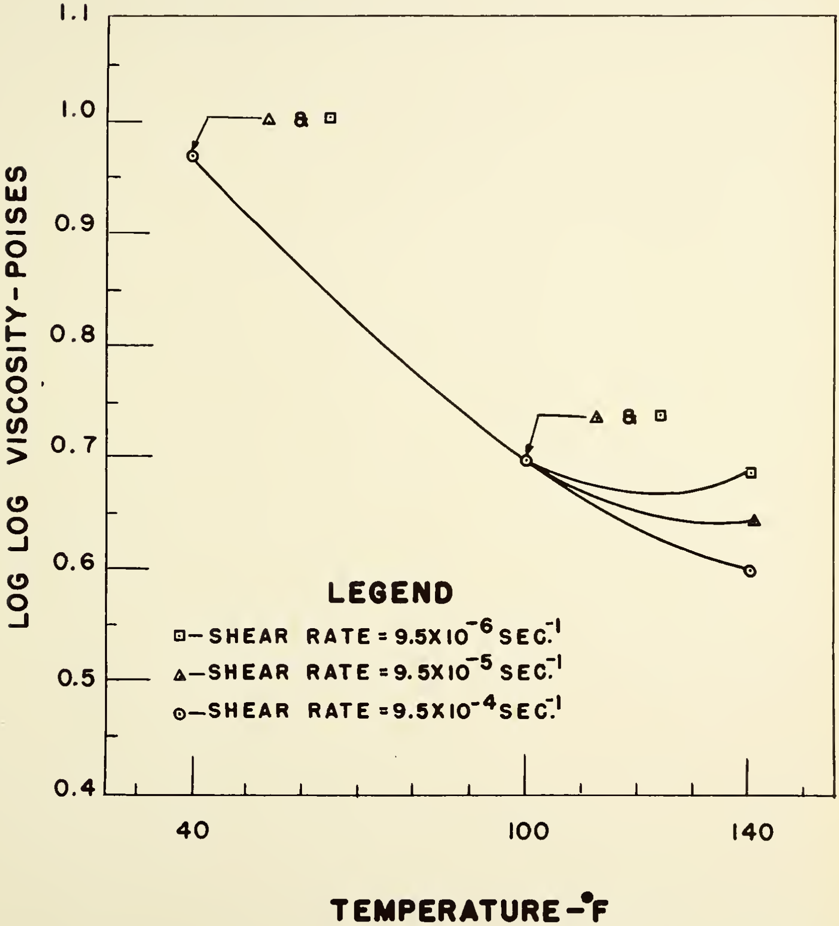

FIGURE 4

RELATIONSHIP BETWEEN TEMPERATURE AND VISCOSITY AT VARIOUS SHEAR RATES FOR ASPHALT C

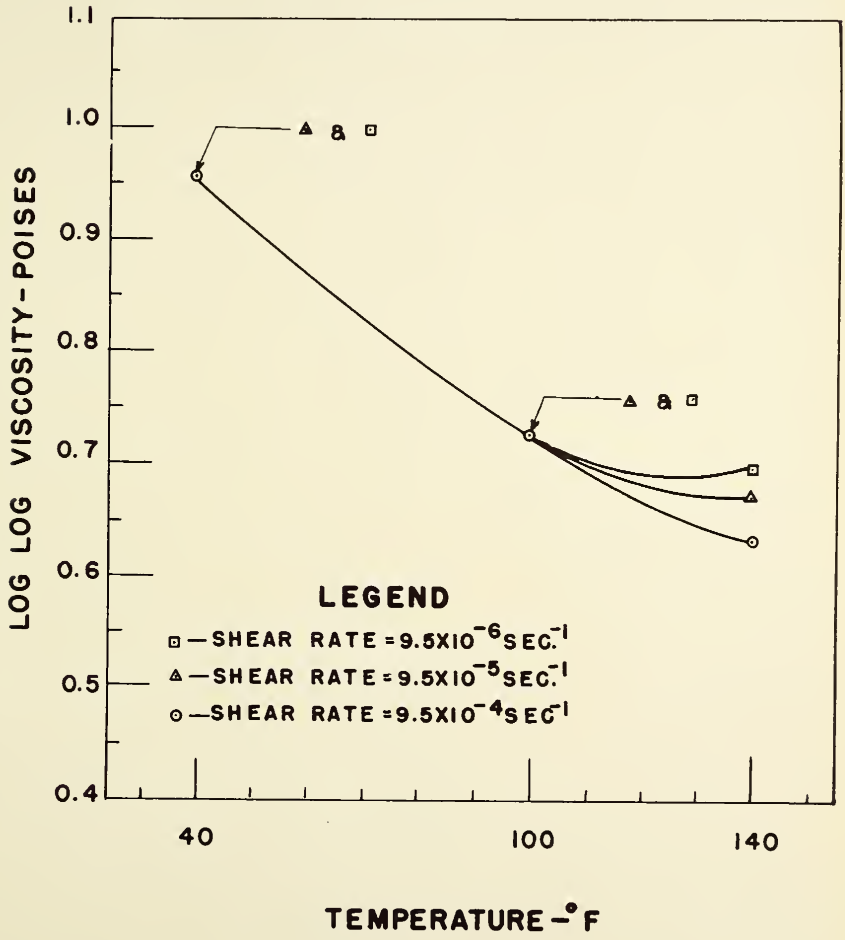

FIGURE 5

RELATIONSHIP BETWEEN TEMPERATURE AND VISCOSITY AT VARIOUS SHEAR RATES FOR ASPHALT D

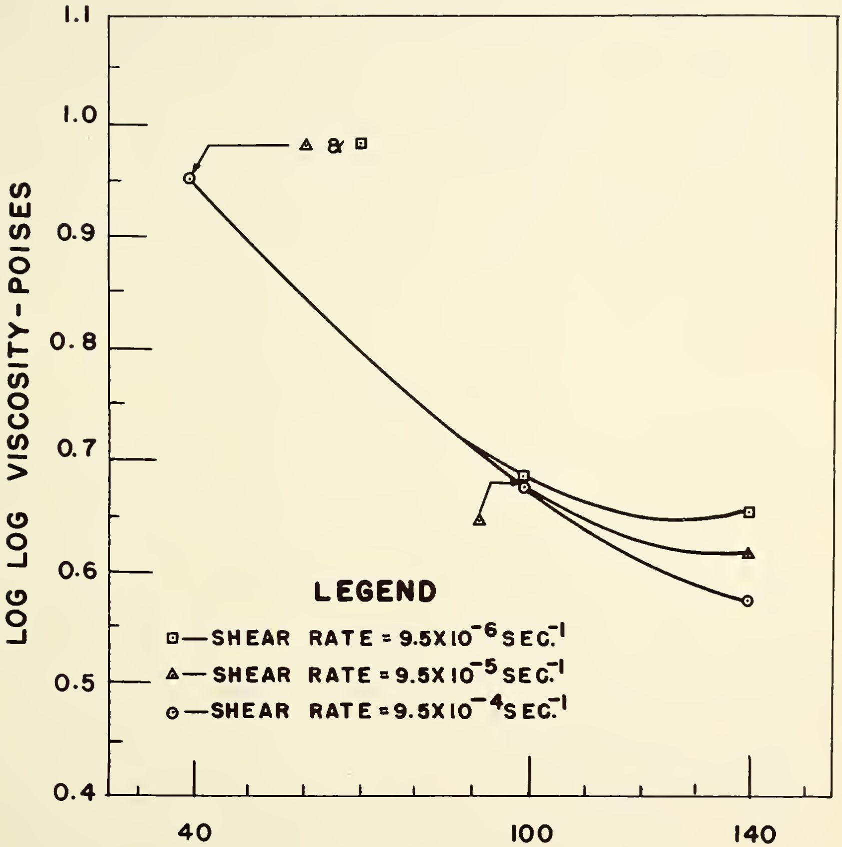

FIGURE 6

In order to evaluate temperature susceptibility of the various asphalts it was necessary to use only the line in Figures 4, 5, and 6 representing the temperature range of $40^{\circ}F$ to $100^{\circ}F$. For this temperature range, the general expression relating temperature and viscosity is $\log \log \mu = mT + c$ where μ = viscosity in poises, T = temperature $^{\circ}F$, c = a constant and m = the slope of the line which in turn is a measure of temperature susceptibility of the asphalt. Thus m = $\frac{\log \log \mu_1 - \log \log \mu_2}{T_1 - T_2}$. Temperature susceptibility evaluated in this manner for the various asphalts is presented in Table 4. Asphalt A has the lowest temperature susceptibility. Asphalt D is the most temperature susceptible, while asphalt B is only slightly less temperature susceptible. Asphalt C has an intermediate value of temperature susceptibility.

Unconfined Compression Tests

The results of the unconfined compression tests performed on the various mixtures are presented in Table 5 and shown graphically in Figures 7, 8, 9, and 10 where the log of the compressive strength in psi is plotted against the temperature in degrees Fahrenheit for the different rates of deformation used in the tests. The resulting plots are quite linear. The general expression for these relationships is: $\log \sigma = mT + C$ ~~log σ = uncon-~~ where σ = unconfined compressive strength in psi, T = temperature in $^{\circ}F$, C = constant, and m = the slope of the line which in turn is a measure of the effect of temperature upon the compressive strength of the mixture.

Thus $m = \frac{\log \sigma_1 - \log \sigma_2}{T_1 - T_2}$.

The temperature susceptibility values expressed in this manner for each mixture and each rate of deformation are presented in Table 6. It

Table 4

Temperature Susceptibility of the Various Asphalts

Evaluated Between $40^{\circ}F$ and $100^{\circ}F$

ASPHALT	TEMPERATURE SUSCEPTIBILITY*
A	0.00380
B	0.00463
C	0.00400
D	0.00465

$$\text{*Temperature Susceptibility} = \frac{\text{Log log viscosity @ } 40^{\circ} - \text{Log log viscosity @ } 100^{\circ}}{100^{\circ} - 40^{\circ}}$$

Table 5

Unconfined Compression Test Results

Temperature °F	Rate of Deformation in./min.	Unconfined Compressive Strength, psi. Asphalt in mixture A	B	C	D
40	.002	445	841	529	755
	.02	660	1152	822	1035
	.2	1045	1863	1228	1836
100	.002	29	35	30	11
	.02	71	70	51	53
	.2	128	143	115	115
140	.002	10	4	3	3
	.02	23	11	14	13
	.2	41	27	24	14

RELATIONSHIP BETWEEN TEMPERATURE AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS RATES OF DEFORMATION FOR MIXTURE USING ASPHALT A

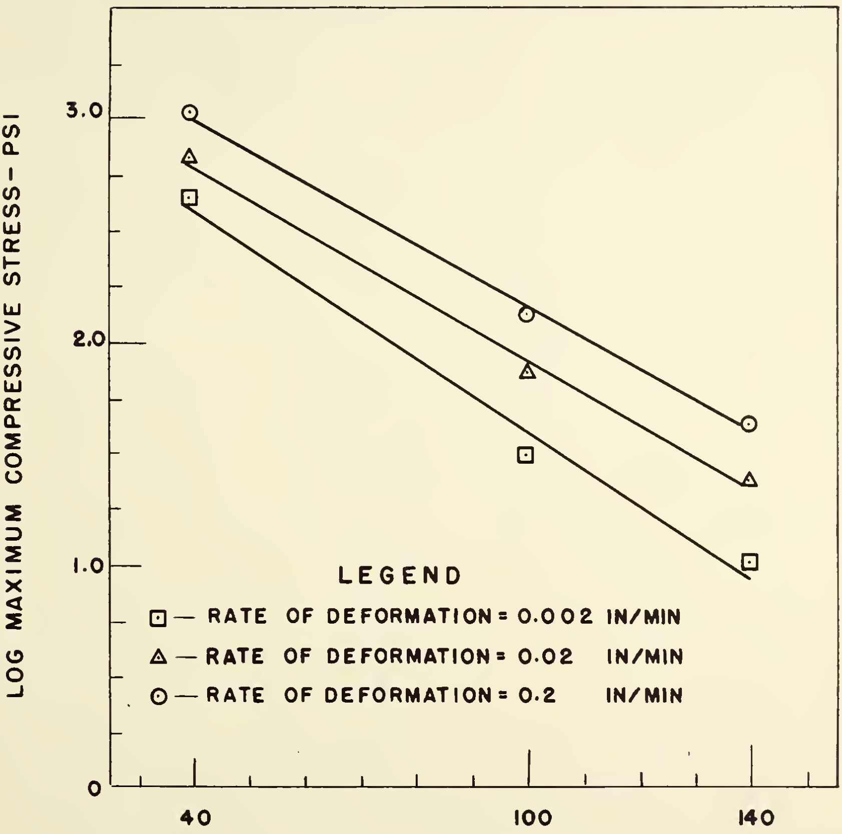

FIGURE 7

RELATIONSHIP BETWEEN TEMPERATURE AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS RATES OF DEFORMATION FOR MIXTURE USING ASPHALT B

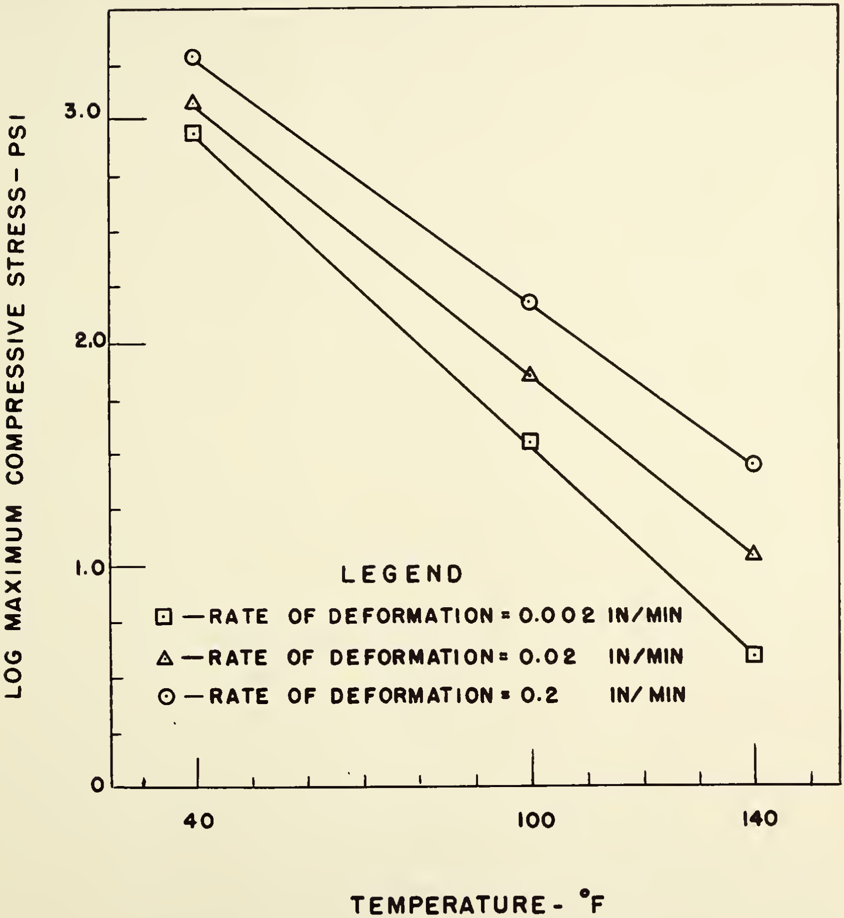

FIGURE 8

RELATIONSHIP BETWEEN TEMPERATURE AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS RATES OF DEFORMATION FOR MIXTURE USING ASPHALT C

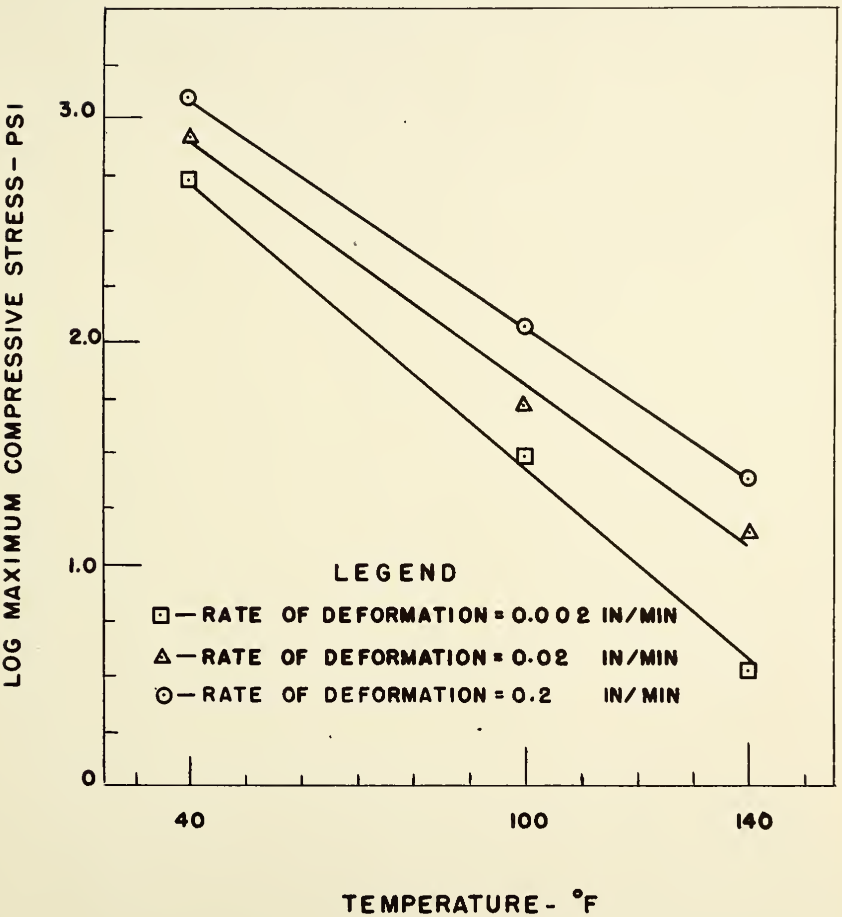

FIGURE 9

RELATIONSHIP BETWEEN TEMPERATURE AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS RATES OF DEFORMATION FOR MIXTURE USING ASPHALT D

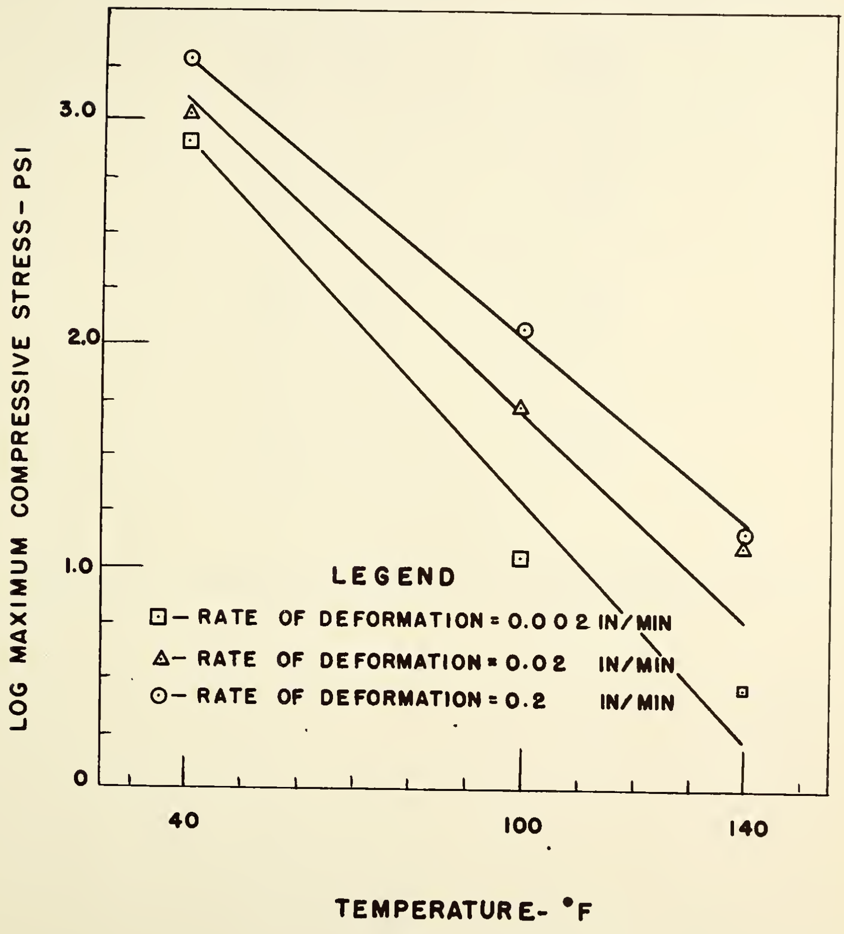

FIGURE 10

Table 6

Temperature Susceptibility of the Different Mixtures

Evaluated at the Various Rates of Shear

ASPHALT	RATE ($SEC.^{-1}$)	TEMPERATURE SUSCEPTIBILITY*
A	9.5×10^{-6}	0.0170
A	9.5×10^{-5}	0.0150
A	9.5×10^{-4}	0.0145
B	9.5×10^{-6}	0.0234
B	9.5×10^{-5}	0.0203
B	9.5×10^{-4}	0.0184
C	9.5×10^{-6}	0.0216
C	9.5×10^{-5}	0.0187
C	9.5×10^{-4}	0.0171
D	9.5×10^{-6}	0.0248
D	9.5×10^{-5}	0.0212
D	9.5×10^{-4}	0.0208

$$\text{*Temperature Susceptibility} = \frac{\text{Log Stress @ } 40^\circ - \text{Log Stress @ } 140^\circ}{140^\circ - 40^\circ}$$

can be seen that the mixture strengths become less susceptible to changes in temperature as the rates of deformation increase. This is as one would expect since the mixtures act less plastic in nature at higher rates of deformation.

When comparing the temperature susceptibility of the four mixtures, it can be seen that the mixture utilizing asphalt A is the least temperature susceptible at all rates of deformation. The mixture that has asphalt D incorporated in it is the most temperature susceptible at all rates of deformation. Mixtures composed of asphalts B and C have intermediate ranges of temperature susceptibility.

It can be observed in Figure 7 that change in the rate of deformation had a slightly greater effect upon compressive strength at 140°F than at 40°F for the mixture using asphalt A. In Figure 10 it can be noted that the mixture using asphalt D was much more sensitive to rate of deformation at 140°F than at 40°. In Figures 8 and 9, which represent mixtures using asphalts B and C, it can be seen that these mixtures are more sensitive to changes in rate of deformation at 140°F than the mixture using asphalt A but that they are less sensitive to changes in rate of deformation at 140°F than the mixture utilizing asphalt D.

Considering the effect of rate of deformation at 140°F upon the compressive strength of the various mixtures and the effect of shear rate at 140°F upon the viscosity of the various asphalts, it ~~is apparent~~ was thought that there ~~must~~ might be an underlying relationship between viscosity of asphalts used in mixtures and the unconfined compressive strength of mixtures using those asphalts which is valid for comparable rates of deformation or shear rate.

Effect of Viscosity Upon Compressive Strength

The combined results obtained from the viscosity determinations and the unconfined compression tests are depicted graphically in Figures 11, 12, 13, and 14 where the log of the unconfined compressive strengths in psi. of the mixtures ~~are~~ is plotted against the log log viscosity in poises of the contained asphalts at the various rates of deformation. From Figure 11, which represents the mixture utilizing asphalt A, it can be seen that the viscosity of the binder had about the same effect upon the compressive strength at all rates of deformation. This is not the case for mixtures using asphalts B, C, and D as shown in Figures 12, 13, and 14.

The compressive strengths of mixtures made with asphalts B, C, and D (see Figures 12, 13, and 14) were affected more by viscosity at all shear rates than were those made with asphalt A. As the shear rate was decreased, the effect of viscosity upon the compressive strength of mixtures utilizing asphalts B, C, and D was more pronounced.

From an examination of the data it is obvious that some factor other than the viscosity of the binder affects the strength of the mixtures, since these strength values vary widely at a fixed viscosity and shear rate. For example, for a log log viscosity value of 0.8 and a shear rate of 9.5×10^{-6} sec.$^{-1}$, the mixture ~~using~~ containing asphalt A had a compressive strength of 75 psi.; the mixture ~~using~~ containing asphalt B had a compressive strength of 199 psi.; the mixture ~~using~~ containing asphalt C had a compressive strength of 95 psi.; and the mixture ~~using~~ containing asphalt D had a compressive strength of 89 psi. These results confirm the statement by Lewis and Welborn (13) "that there is some characteristic of an asphalt other than consistency that causes mixtures made with different asphalts to vary in stability and compressive strength." Although the factor of shear rate was recognized, it was not possible from the data collected in this study to ascertain what this additional factor might be.

RELATIONSHIP BETWEEN VISCOSITY AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS SHEAR RATES FOR ASPHALT A

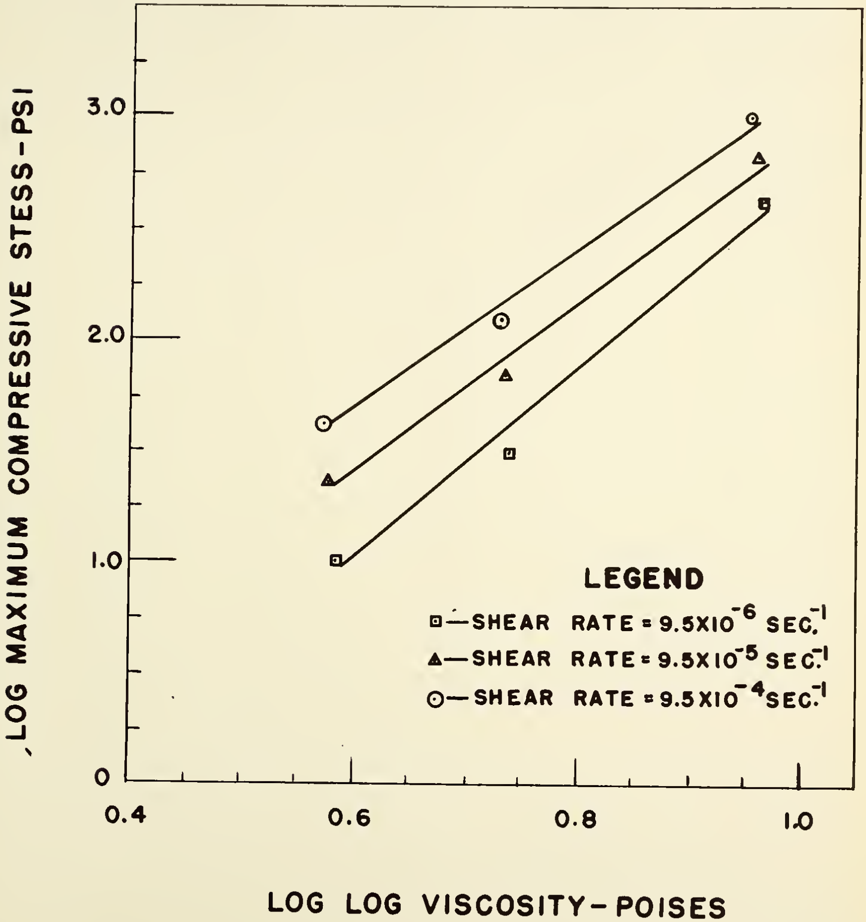

FIGURE 11

RELATIONSHIP BETWEEN VISCOSITY AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS SHEAR RATES FOR ASPHALT B

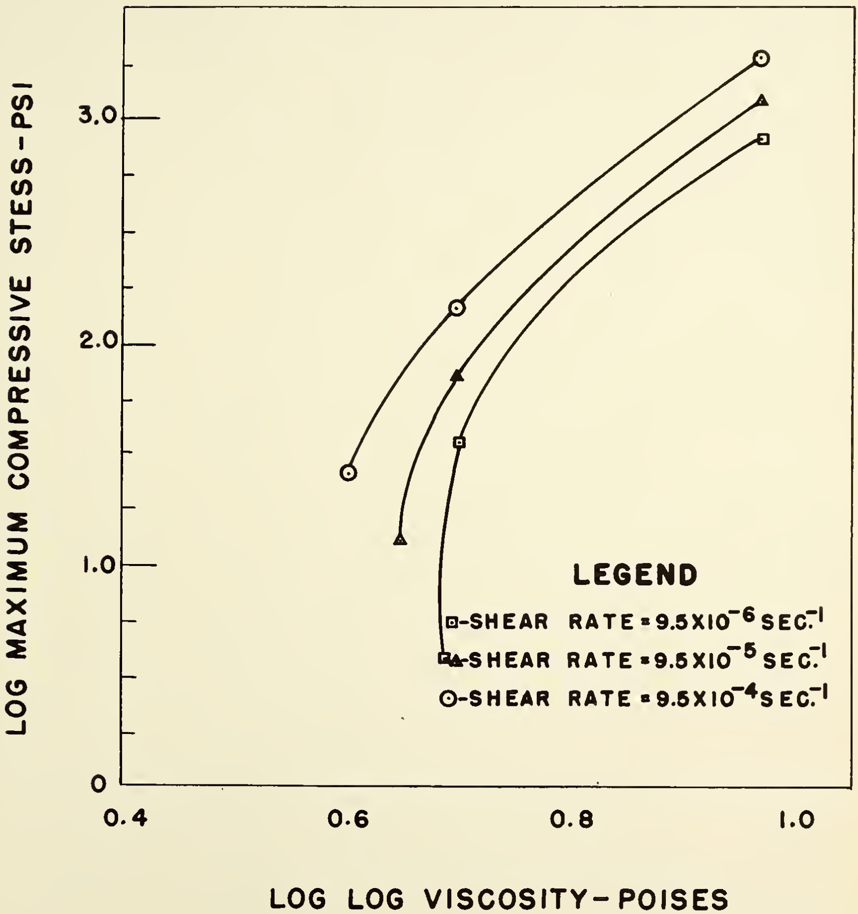

FIGURE 12

RELATIONSHIP BETWEEN VISCOSITY AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS SHEAR RATES FOR ASPHALT C

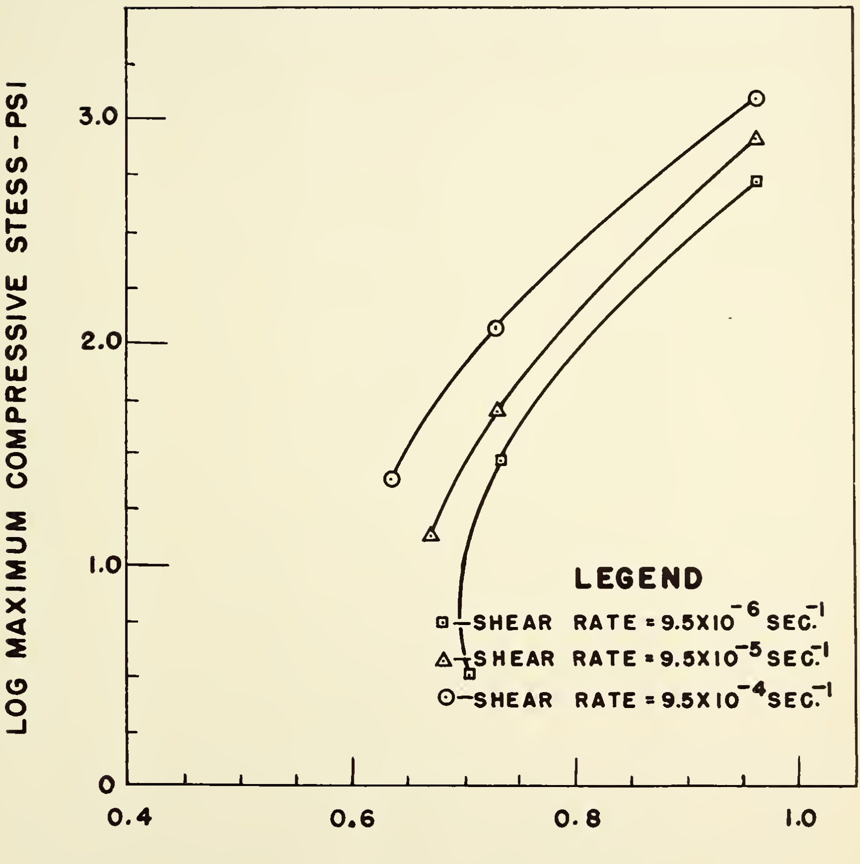

FIGURE 13

RELATIONSHIP BETWEEN VISCOSITY AND MAXIMUM COMPRESSIVE STRESS AT VARIOUS SHEAR RATES FOR ASPHALT D

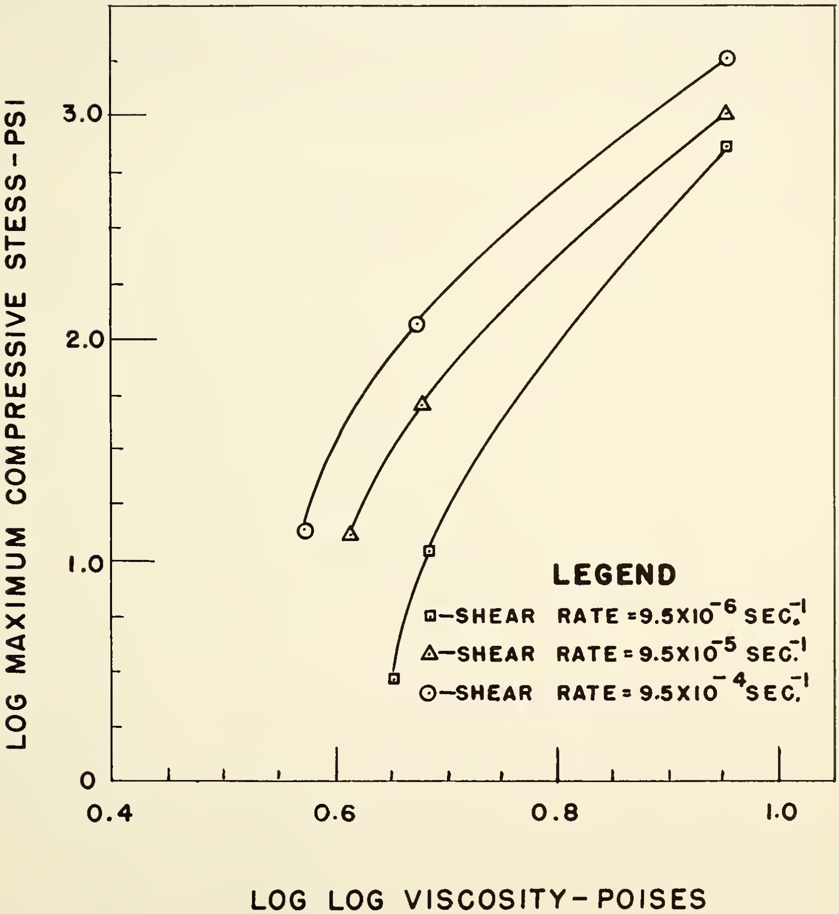

FIGURE 14

SUMMARY OF RESULTS

The aggregate gradation and asphalt content used in this study resulted in a mixture which was more plastic in character than many bituminous concretes. This was desirable for the purposes of this study since it was advantageous to have sheet-asphalt mixture strength dependent to an appreciable degree upon the viscous properties of the asphalts. With these concepts in mind the following summary of results is precented:

1. As demonstrated by the asphalts used in this study, the effect of shear rate upon viscosity can vary from very little to a very marked effect.

2. The effect of shear rate upon ashpalt viscosity varies with temperature as well as with asphalt type. The viscosity of asphalt A was little affected by shear rate at all of the test temperatures used, while the viscosity values of asphalts B, C, and D not only were affected by shear rate at all test temperatures but the effect of shear rate upon viscosity was greater the higher the temperature.

3. For the ranges of shear rate and temperature used in this study, the plot of log unconfined compressive strength in psi. versus temperature in degrees Fahrenheit gave a simple means of evaluating temperature susceptibility of mixtures.

4. The effect of temperature upon the unconfined compressive strength of a mixture can be ascertained qualitatively from the effect of temperature upon the viscosity of the contained asphalt cement.

5. No direct relationship was found between the unconfined compressive strength of sheet asphalt mixtures used in this study and the viscocity of the contained asphaltic binder even though the effects of shear rate were taken into consideration. Thus it is indicated that factors other than

the viscosity of the binder have an effect upon bituminous mixture strength. However, the data of this study do not reveal what these factors may be.

It is felt that further work in which the effects of such variables as surface-chemical reactions, molecular orientation, and steric hardening are recognized would possibly reveal the nature of these unknown factors.

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